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FINAL TECHNICAL REPORT

to the

National Aeronautics and Space Administration

on

STUDY OF THE SOLAR CORONA USING RADIO AND SPACE OBSERVATIONS

NSG-7287, 1 October 1978 to 31 October 1979

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Title of Grant: "Study of the Solar Corona Using Radio and Space Observations"

Author: George A. Dulk, Principal Investigator

In the following we set forth the progress that was made on the tasks set forth under this grant. The work was concentrated in four areas: A) coronal transients, B) coronal magnetic fields, C) energetic electrons in the corona following flares, and D) miscellaneous topics. Work on the various topics was done by the Principal Investigator (G. Dulk), a Research Associate (B. Jackson), and a graduate student Research Assistant (D. Gary). Also collaborating were a number of people from Australia: S. Smerd (until his death on 20 December 1978), K. Sheridan, D. McLean, S. Suzuki, D. Melrose, and S. White. From the U.S., R. MacQueen participated in one of the investigations.

In the following sections, the accomplishments are described by reproducing the abstracts of papers published, in press, or submitted during the year of the grant.

A. Investigation of the Observational and Physical
Characteristics of Coronal Transients

Proc. IAU Symp. 86 (submitted):

RADIO AND WHITE-LIGHT OBSERVATIONS OF CORONAL TRANSIENTS

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ABSTRACT

Optical, radio and X-ray evidence of violent mass motions in the corona has existed for some years but only recently have the form, nature, frequency and implication of the transients become obvious. In this paper I review the observed properties of coronal transients, concentrating on the white-light and radio manifestations. The classification according to speeds seems to be meaningful, with the slow transients having thermal emissions at radio wavelengths and the fast ones non-thermal. I then discuss the possible mechanisms involved in the radio bursts and review the estimates of various forms of energy. It appears that the magnetic energy transported from the Sun by the transient exceeds that of any other form, and that magnetic forces dominate in the dynamics of the motions. The conversion of magnetic energy into mechanical energy, by expansion of the fields, provides a possible driving force for the coronal and interplanetary shock waves.

*Proceedings of the Astronomical Society of Australia
Volume 3 Number 4 pages 249-250 December 1978*

Radio Observations of a Massive, Slow-Moving Ejection of Coronal Material

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G. A. Dulk* *Division of Radiophysics, CSIRO, Sydney*

Studies of coronal transients observed in white-light (Gosling *et al.*, 1976) have shown that fast-moving events ($\lesssim 400 \text{ km s}^{-1}$) are closely associated with flares and with type II and IV radio bursts while slow-moving events are not. We now report the first detection of the radio counterpart of a slow-moving transient. The event of 1974 January 21 is shown to be visible on maps of the quiet Sun made at a frequency of 80 MHz.

Proceedings of the Astronomical Society of Australia
Volume 3 Number 4 pages 251-252 December 1978

On the Relative Importance of Radiative, Mechanical and Magnetic Energy Release of Flares

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Introduction

For many years we have had evidence from solar radio bursts of violent mass motions in the solar corona: type II bursts reveal the passage of shock waves through the solar corona, and moving type IV bursts show that plasma and magnetic field travel to great distances without any sign of slowing down.

More recently white-light coronagraph observations from satellites have revealed the ejection of large masses of gas from the Sun. So far it has been possible to compare data for white-light transients and moving type IV bursts in only two cases (Stewart *et al.* 1974a,b), but it seems likely that these phenomena are sometimes — perhaps often — closely related. Similarly a relationship between white-light transients and type II bursts has been found (Gosling *et al.* 1976), but the physical nature of this relationship has not been elucidated.

These shock waves and mass motions represent a release of energy, initiated by solar flares, into the solar corona; this energy is revealed as the mechanical energy of shock waves, and as the kinetic energy, potential energy and enthalpy of the masses of moving gas. Since the coronal plasma is a magnetized plasma, these mass motions also entail the transport out through the corona of magnetic energy, and because the magnetic fields so transported must eventually expand under their own magnetic pressure against the surrounding ambient corona or solar wind, much of the magnetic energy transported by mass motions will be transformed into mechanical energy high in the corona. The radio data enable us to estimate this secondary magnetic energy release.

Solar Physics (to be submitted):

The Association of Type III Bursts and Coronal Mass Ejection Transients

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and

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Abstract

Isolated metric Type III radio bursts recorded during the Skylab period (from May 1973 to February 1974) are observed to be more frequent than average prior to some mass ejection transients. There is a broad peak in the number of bursts 8-hours prior to the time of the main portion of the mass ejections observed with the Skylab coronagraph. The Type III bursts within this peak generally arise from the region near the eventual transient, i.e. within 20° of the solar position angle of the centre of the mass ejections. The peak in burst activity for individual events is shown to correspond in time with the onset of the first observed motion of the transient forerunners. Those events that have well-documented surface manifestations can be shown to come from active regions where magnetogram data show bipolar regions of strong magnetic field increasing in size over a period of days. This strongly suggests that an emerging flux mechanism is involved in supplying the energy necessary to expel the transient material.

B. Investigation of the Ambient Coronal Magnetic Field
Above Active Regions

Proc. Astron. Soc. Aust. (in press):

Evidence for Extreme Divergence of Open Field Lines from
 Solar Active Regions

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In this paper we review the evidence on the structure of the open magnetic field lines that emerge from solar active regions into interplanetary space. The evidence comes mainly from the measured sizes, positions and polarization of Type III and Type V bursts, and from electron streams observed from space. We find that the observations are best interpreted in terms of a strongly-diverging field topology, with the open field lines filling a cone of angle $\sim 60^\circ$.

The Position and Polarization of Type III Solar Bursts by G.A. DULK, CSIRO Division of Radiophysics also Department of Astro-Geophysics, University of Colorado and S. SUZUKI, CSIRO Division of Radiophysics - We study the position and polarization of type III bursts in the range 24-220 MHz, concentrating on bursts that continue to frequencies lower than 24 MHz, i.e. bursts occurring on field lines extending from active regions into interplanetary space. The 997 bursts studied fall into two classes: fundamental-harmonic (F-H) pairs and "structureless" bursts with no visible F-H structure.

The major conclusions of our study are:

- (1) The large source sizes and rapid increase of source size with height implies that the open field lines from active regions diverge strongly; this is in general accord with observations of interplanetary electron bursts and with calculations of potential fields.
- (2) The center-to-limb decrease in polarization of H-radiation is not as predicted by simple theory assuming homogeneous sources and radial field lines. However a rapid divergence of the field lines can result in decreased polarization, allowing theory and observations to be reconciled.
- (3) The constancy of polarization with f implies that the ratio of gyro-magnetic to plasma frequency f_B/f_p , the Alfvén speed v_A and the plasma beta are constant with height on the open field lines above active regions. From theory and the observed polarization of H-radiation we find average values: $\langle f_B/f_p \rangle \approx 0.22$, $\langle v_A \rangle \approx 1400 \text{ km s}^{-1}$ and $\beta \approx 0.02$.
- (4) The magnetic field strength B derived from the H-polarization decreases from an average of $\approx 8 \text{ G}$ at the 100 MHz plasma level (at $R \approx 1.2 R_0$) to $\approx 1 \text{ G}$ at the 12 MHz plasma level (at $R \approx 2.5 R_0$), with most individual values within a factor of 2 from the averages.

C. The Properties of Energetic Electrons in the Corona at the Time of Flares

*Proceedings of the Astronomical Society of Australia
Volume 3 Number 4 pages 243-247 December 1978*

Radio Evidence on the Particle Distribution Functions in the Corona following Flares

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In this paper we summarize the results of radio studies of the distribution functions (number, energy distribution and pitch angle distribution) of the energetic particles that are produced at the time of solar flares. We consider the clues and constraints they impose on the mechanisms of acceleration, bearing in mind that radio evidence implies that there are at least two stages of acceleration in many flares.

In the following sections we discuss the distribution functions of the particles resulting from (a) first phase acceleration, (b) first and/or second phase and (c) second phase acceleration. Table 1 summarizes the results.

TABLE 1

Particle distribution functions for various types of radio bursts

Burst	Radiation mechanism	Total number of particles	Energy range, energy distribution	Pitch angle distribution	Remarks
(a) First (Flash or Impulsive) Phase					
Type III at $R \geq 1.1 R_{\odot}$	Plasma	~ 10 bunches $10^{11} - 10^{12}$ per bunch	10 - 100 keV, gap	Forward cone of angle $\sim 20^\circ$	Fast electrons have outpaced slow
Microwave impulsive	Gyro-synchrotron	$\sim 10^{11} - 10^{12} > 10$ keV	10 keV \sim 1 MeV, power law with $\gamma = 3$ to 5	Nearly isotropic?	Most emission from e^- of $E \geq 100$ keV
	Gyro-synchrotron	$\sim 10^{11} - 10^{12}$	$T_e \sim 10^8 - 10^9$ K Maxwellian	Nearly isotropic?	
(b) First and/or Second Phase					
Type II	Plasma	?	Plateau or gap	Anisotropic	
Flare continuum (FCM)		See below			
(c) Second Phase					
Microwave IV	Gyro-synchrotron	$10^{11} - 10^{12}$	0.5 - 5 MeV, Power law with $\gamma \approx 2$ to 3	Nearly isotropic?	e^- trapped in low coronal loops
Moving type IV					
(a) Advancing front	Gyro-synchrotron	$\sim 10^{11} > 1$ MeV	1 - 3 MeV, power law with $\gamma \approx 5$ to 10	Nearly isotropic?	Rare. Moves outward with shock
(b) Isolated source	Gyro-synchrotron	$\sim 10^{11} > 0.1$ MeV	0.1 - 1 MeV, power law with $\gamma \geq 4$	Nearly isotropic?	Plasmoids with $B \sim 3$ to 10 G
Flare continuum (FC II)	Plasma	$\geq 10^{11} \geq 10$ keV	Plateau or gap	Loss cone	Sometimes starts with III's (FCM)
	Gyro-synchrotron?	$\sim 10^{11} > 0.5$ MeV	0.5 - 1 MeV, power law with $\gamma \approx 7$	Nearly isotropic?	e^- trapped in high coronal loops

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THE GYROSYNCHROTRON EMISSION FROM QUASI-THERMAL ELECTRONS AND APPLICATIONS TO SOLAR FLARES

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Received 1978 November 13; accepted 1979 July 2

ABSTRACT

We present theoretical results on the gyrosynchrotron radiation from electrons with a Maxwellian energy distribution. We review the analytical expressions for the gyromagnetic absorption coefficient and find two which cover the range of interest for microwave emission from solar flares, i.e., frequencies ω to $\sim 100\Omega_e$ and temperatures T_e to $\sim 10^8$ K. Numerical calculations are used to check the analytic expressions and to derive simplified empirical formulae which relate the observable characteristics of the radiation to the temperature and magnetic field in the source.

We apply the results to the sources of impulsive microwave and hard X-ray bursts from solar flares. For an isothermal source the theory predicts a microwave spectrum where the flux density rises as f^2 at low frequencies, maximizes at some frequency f_{peak} , and falls very rapidly thereafter; this shape fits the observed spectra qualitatively. The optical depth τ of the source varies rapidly with f , with $\tau = 1$ at $f \approx f_{\text{peak}}$. For $T_e \gtrsim 10^8$ K we derive the relation $f_{\text{peak}} \propto T_e^{0.7} B$, which allows a direct estimate of the magnetic field B in the impulsive burst source if the temperature is known—for instance, from hard X-ray observations. For the impulsive burst of 1972 May 18, reported by Hoyng and Stevens, we find that the microwave and hard X-ray data are well fitted by a model source with $T_e \approx 2.3 \times 10^8$ K, $B \approx 370$ gauss, $n_e \approx 2 \times 10^9 \text{ cm}^{-3}$, and scale length $L \approx 8600$ km.

Subject headings: Sun: flares — Sun: radio radiation — Sun: X-rays — synchrotron radiation

Astron. and Astrophys. (submitted):

The Position and Polarization of Type V Solar Bursts

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Summary. The position and polarization of Type V bursts and the preceding Type III bursts have been observed with the 24-220 MHz spectropolarimeter, the 8-8000 MHz spectrograph and the three-frequency radioheliograph at Culgoora. We have measured the polarization, frequency range, source position, source movement, source size and brightness temperature of the Type V and the Type III bursts, in many cases for both the fundamental (F) and harmonic (H) components of the III.

The major new result of our study is the discovery that more than half (25 out of 41) of the Type V bursts which follow F-H IIIs are circularly polarized in the sense opposite to that of the IIIs. Few (2 out of 41) are polarized in the same sense as the IIIs, while the remainder (14 out of 41) are of zero or mixed polarization. The observed degree of polarization of Type V radiation (typically 0.05 to 0.10) supports earlier suggestions that the radiation is due to plasma emission at the second harmonic.

We examine three possible reasons for the reversal of polarization from Type III to Type V: (a) that the magnetic field direction in the two sources is of opposite polarity; (b) that mode coupling at transverse points changes from strong in the Type III to weak in the Type V; (c) that the mode of emission changes from o-mode to x-mode. We conclude that (a) is possible but improbable, (b) is very unlikely and (c) seems to be favourable.

From the theory of the polarization of harmonic plasma radiation we determine the conditions needed for a change from o-mode to x-mode: the angular distribution of Langmuir waves must change from nearly unidirectional in the Type III source, with most wave vectors at angles $\lesssim 30^\circ$ from the magnetic field direction, to a more widespread distribution in the Type V source, with angles $\gtrsim 60^\circ$.

D. Miscellaneous

Proc. IAU Symp. 91 (submitted):

RADIO OBSERVATIONS OF CORONAL HOLES

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ABSTRACT

Coronal holes have been observed on several occasions with the 80 and 160 MHz radioheliograph at Culgoora. At 160 MHz the holes invariably appear as areas of low brightness, either on the disk or at the limb. At 80 MHz holes on the limb always appear less bright than their surroundings but on the disk they frequently appear brighter.

The simplest interpretation is that the coronal temperature in holes near the 80 MHz critical density ($8 \times 10^7 \text{ cm}^{-3}$) is higher than in normal quiet regions, but that the density at this level is lower.

Proc. Astron. Soc. Austr. (in press):

Comparison of Radioheliograph, Coronagraph, and K-Coronameter
 Observations of a Coronal Streamer

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We compare observations of a large coronal streamer made with the 80 MHz Culgoora radioheliograph, the K-coronameter on Mauna Loa and the white light coronagraph on Skylab. The various measurements are not in agreement, and this raises fundamental questions about the nature of the corona ^{and} wave propagation through a streamer structure. The comparisons also indicate how precise data from the heliograph may contribute to a better understanding of these processes.

Proc. Astron. Soc. Austr. (in press):

Evidence for a Peak in the Number of Isolated Type III
Bursts prior to Large Solar Flares

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Most if not all metre-wave Type III bursts appear to be associated with solar active regions (e.g. Duncan 1977). There is a well-known association of Type III bursts and flares within a few minutes of the onset of the brightenings seen in H α (Wild et al. 1954). Early descriptions of these observations were given by Malville (1961) (or see Kundu (1965) for review). More recently Jackson et al. (1978) have reported the occurrence of a broad maximum of Type III bursts 10 to 5 h prior to mass ejection transients seen by the white light coronagraph on Skylab.

Here we report on evidence for a broad maximum in the number of isolated metre-wave Type III bursts 5 h prior to the time of the large solar flares observed in H α between May 1973 and February 1974. This maximum is more pronounced when Culgoora heliograph observations permit identification of the Type III bursts associated with the flaring region.